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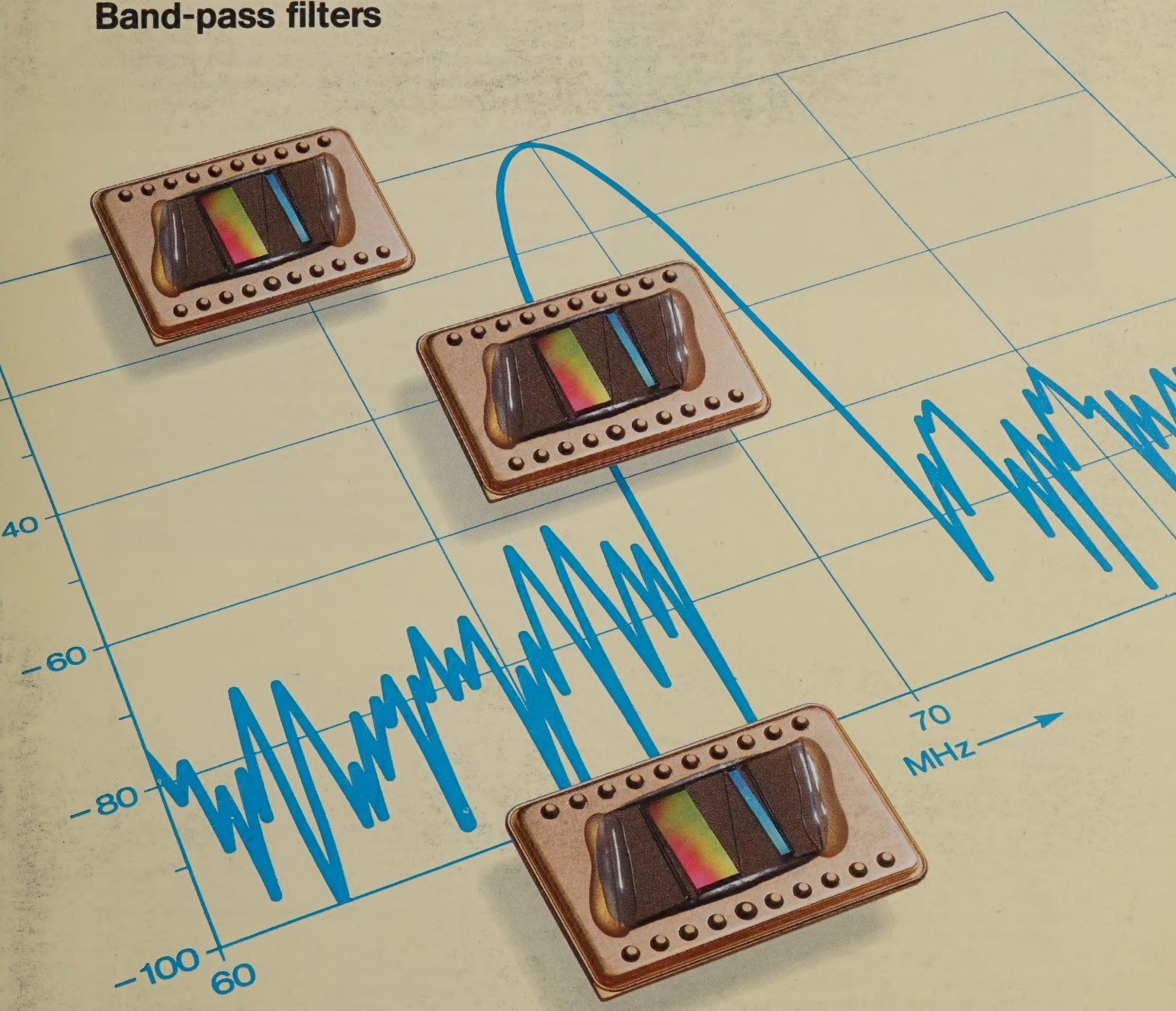
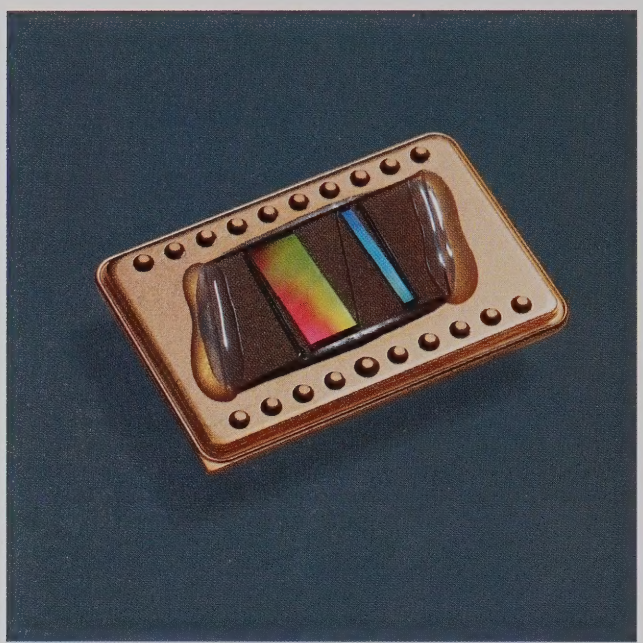
Surface Acoustic Wave Components for Professional Telecommunications Engineering

Band-pass filters



Spectrum-Shaping SAW Filters for Digital Radio Link Systems



Precise filters with a frequency range from 10 MHz to 1 GHz can be produced by depositing microstructures onto piezoelectric substrates. These components, which are based on the excitation and propagation of surface acoustic waves, allow flexible realization of signal-matched transfer functions. They can be manufactured reproducibly, possess long-term stability and are miniaturized. Sophisticated design and production methods now meet the rigorous demands on the accuracy of the transfer function of spectrum-shaping filters in digital radio relay systems.

In this paper, surface acoustic wave (SAW) filters for systems with 2 and 140 Mbit/s are described.

Spectrum-shaping filters

Due to the advantages of digital signal transmission this technology has gained a foothold also in terrestrial radio link applications in recent years. Suitable modulation of the transmitter signal and spectrum-shaping filtering techniques are used to match the actual bandwidth of the digital signal to the system's inherent requirements in terms of bandwidth economy. Optimum reception requires filtering of the signal spectrum in line with the Nyquist criterion. However, the arrangement of the spectrum-shaping filters in the IF stages of the transmitters and receivers, per se a favorable solution, entails restrictions if these filters have to be implemented in the traditional LC technology, because the accuracy required of the transfer functions can be achieved only with difficulty; besides, the development and adjustment of such filters are expensive. For such cases, the SAW filters developed using the latest techniques suggest themselves as an optimum solution.

References

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Surface acoustic waves

Surface acoustic waves are elastic waves propagating at the surfaces of solids with elliptical particle displacement which decays exponentially with increasing depth [1, 2]. Of all elastic waves capable of propagating in solids, the Rayleigh or surface wave exhibits the lowest propagation velocity. The propagation of surface waves is not dispersive and is almost free of attenuation.

The waves are excited by "interdigital" structures which act as effective transducers between electric signals and acoustic waves on piezoelectric substrates. An interdigital transducer consists of interleaved comb-like electrodes ("fingers") which are photodeposited in the form of a thin metal layer on a highly polished piezoelectric substrate. A simple idea of how an interdigital transducer works can be obtained by assuming that both the exciting electric field in the finger overlap region and the associated mechanical tension are sinusoidal **(Fig. 1).** Due to the piezoelectric effect, a needle-shaped electrical impulse applied to the transducer generates a wave packet which is emitted bidirectionally from the transducer. At a propagation velocity v of the surface wave, the values for the duration of a period T and of a packet τ of the wave are obtained from period p and length $L = Np/2$ of the transducer, where N is the number of finger overlaps.

The analysis of the frequencies contained in the wave packet shows that for period T the maximum of the transfer function lies at the center frequency $f_0 = 1/T = v/p$. The constant envelope and the finite duration τ of the wave packet results in a sinx/x-shaped frequency spectrum which exhibits a width $B = 1/\tau = 2\ f_0/N$ at an amplitude drop of −4 dB.

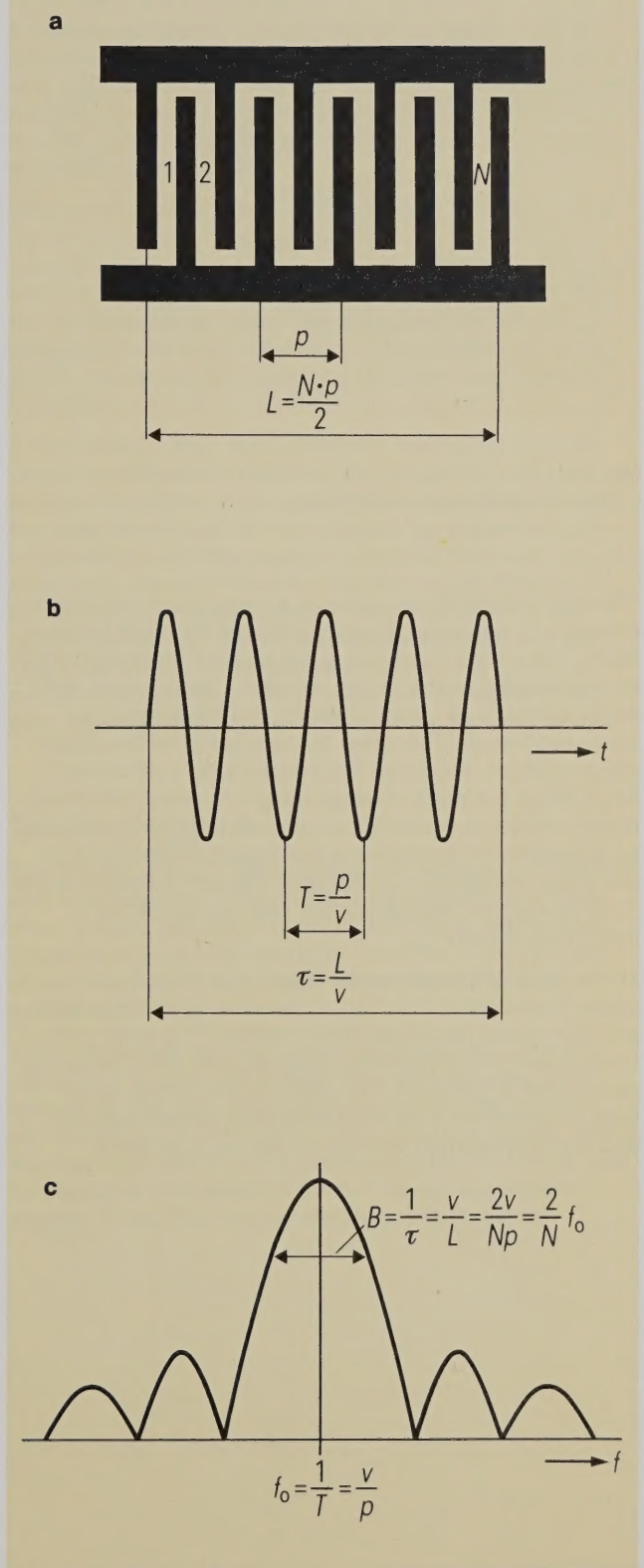


Fig. 1
Idealized excitation of a surface wave by an interdigital transducer
a) Transducer geometry
b) Amplitude of the wave
c) Magnitude of the frequency spectrum

B	Bandwidth	p	Cycle
f_0	Center frequency	T	Duration of a wave cycle
L	Length	τ	Duration of the wave packet
N	Number of finger overlaps	v	Velocity of propagation

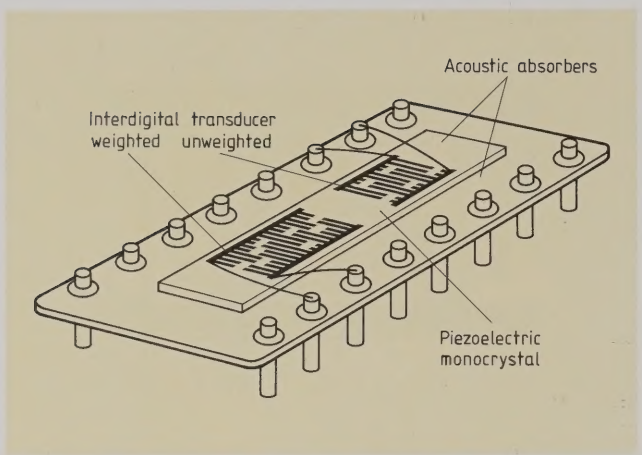


Fig. 2
Surface acoustic wave (SAW) filter

The sinx/x-shaped response of a transducer with finger overlaps of equal length is insufficient for most applications. The emitted surface wave power can be adjusted by the lengths of the finger overlaps. Transducers with finger overlaps of unequal length are designated as weighted transducers **(Fig. 2).** As a result of the piezoelectric effect, a receive transducer with sufficiently large finger overlaps of equal length (unweighted transducer) converts the surface wave distribution generated by a weighted transducer into a signal proportional to the finger overlaps. The resulting transfer function of the SAW filter is the product of the transfer functions of both transducers.

In the case of two $p/4$-wide fingers per transducer cycle, the transfer function of the filter is symmetrical and the phase response asymmetrical. For symmetrical transducers the phase response is linear and the group delay time is constant. The value of the group delay time is determined by the transducer center spacing and the propagation velocity of the surface wave.

In the case of four fingers with a width of only $p/8$ per transducer period **(Fig. 2),** suitably large finger overlaps in the weighted transducer allow any desired transfer function to be obtained. Since similar finger metallization edges appear at $p/4$ intervals, reflected surface waves, which may lead to distortions in the filter transfer function, cancel out. Filters of this design also have transmission bands at odd multiples of the fundamental frequency.

Effective transfer function

The load impedance and the frequency-dependent transducer impedance cause a frequency-dependent voltage drop and a signal attenuation resulting from filter mismatch (insertion loss), which in turn makes the transfer function assume its effective value: the previously described relationship between filter geometry and transfer function no longer applies exactly.

By inserting circuit elements designed to match the transducer impedances to the load resistances, the filter insertion loss can be reduced. In the simplest case, a coil is connected in series or parallel with each transducer, which is made to resonate at the filter center frequency with the capacitance of the interdigital structure. The transfer function resulting from complete matching is determined essentially by the resonating circuit and not by the transducer geometry. The insertion loss then attains a minimum of 6 dB, because every transducer emits bidirectionally and thus loses half of its power to the wave absorbers which are designed to prevent reflections from the substrate ends **(Fig. 2).**

However, since the bandwidth of the resonant circuit must not be less than that of the transducer, it is impossible to obtain an insertion loss below a certain minimum.

The conversion of electric signals to surface waves and vice versa in the interdigital transducers of an SAW filter gives rise to a spurious signal, the triple transit echo, which follows the filter impulse response at an interval equaling double the delay time τ_0 between the transducers. It undergoes two more conversions than the main signal and is thus weakened by double the filter insertion loss. The triple transit echo has a degrading effect on the filter transfer function. A Fourier analysis of the degraded filter impulse response shows a ripple of period $1/(2\tau_0)$ in both magnitude and group delay time.

For these reasons, optimal matching of the SAW filter is not attempted. The minimum attainable filter insertion loss is determined by the permissible ripple in the transfer function, the filter bandwidth and the substrate material.

The substrate

The most frequently used substrates for SAW filters are the piezoelectric single-crystal lithium niobate ($LiNbO_3$) and quartz. In these anisotropic crystals, surface waves are propagated preferentially in certain directions relative to the crystal axis.

Due to their greater piezoelectric coupling constants as well as their higher temperature coefficient of about −90 ppm/K, suitable $LiNbO_3$ cuts are used almost exclusively for filters with greater bandwidths ($B/f_0 > 5\%$). Besides a low piezoelectric coupling constant, ST,X quartz has a negligibly small linear temperature coefficient and a low parabolic temperature response (only 150 ppm over a temperature range of ± 70 K). For this reason, quartz is a good choice for narrowband filters.

The propagation velocity of the surface wave lies in the region between 3000 and 4000 m/s for the substrates mentioned. With the production technology imposing a minimum finger width of 1 µm and a substrate thickness of 0.5 mm, the implementation range for SAW filters lies between 10 MHz and 1 GHz.

Design approach

A simple model, the impulse model, suggests a linear relationship between the lengths of the finger overlaps of a weighted transducer and the filter transfer function. For the interdigital transducers with a given number of fingers, a linear optimization approach ensures an optimum filter design.

When implemented, a filter designed in this way would not attain its optimum transfer function because second-order effects which the impulse model does not take into account occur during excitation and propagation of the surface wave. The second-order effects of relevance here are included in an extended model [3] which can be used to evaluate the degraded transfer function.

A "correction" filter with a transfer function that represents the difference between the degraded and optimal transfer functions is designed and then used to modify the ideal filter so as to compensate for these second-order effects [4]. This ensures that the filter very largely attains its optimum transfer function again. Effects occurring outside the impulse response of the interdigital transducer cannot be compensated in any way. The triple transit echo can be reduced only by transducer mismatch and the concomitant increase of the filter insertion loss.

Technology

The fingers in each filter – there are between a hundred and a thousand of them – must be produced without short circuits and interruptions. The finger widths and thicknesses must be accurate to within a few percent since they have a significant effect upon the filter center frequency.

Thus, to ensure reproducibility in production, use is made of the most up-to-date photolithographic processes of the type developed for generating microstructures for VLSI circuits. They allow the scatter range for the finger width to be narrowed down to 50 nm, that for the layer thickness to 5 nm. The corresponding scatter of the filter center frequency is 20 ppm!

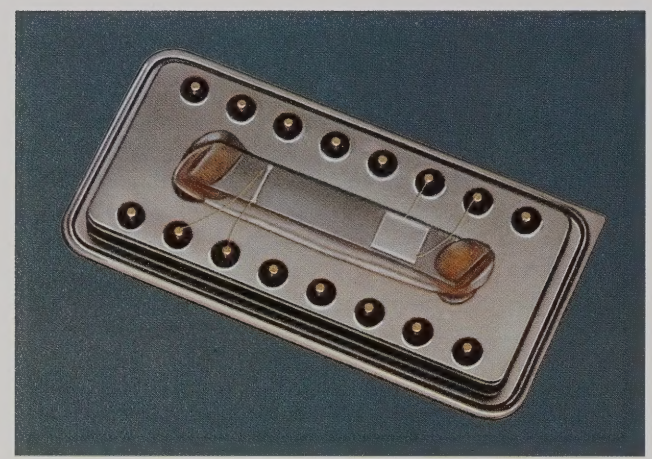


Fig. 3
Surface acoustic wave (SAW) filter for 140 Mbit/s digital radio link systems

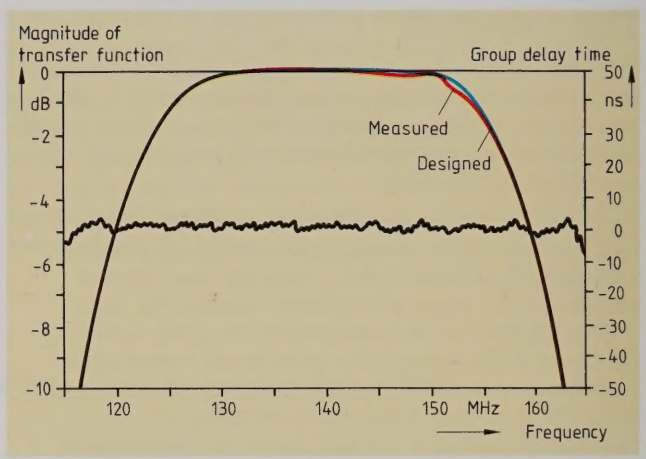


Fig. 4
Magnitude and group delay time of the transfer function of a spectrum-shaping filter for the demodulator stage of a 140 Mbit/s digital radio link system

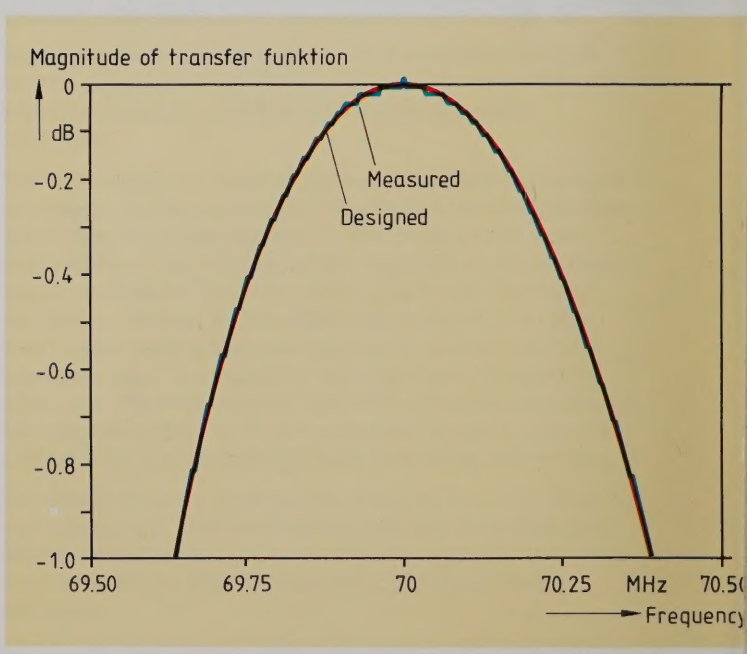
Spectrum-shaping filters for a 140 Mbit/s radio link system

The highest bit rate planned for transmitting digital signals via radio link systems is 140 Mbit/s, which is sufficient for 1920 telephone channels. By means of a 16-stage quadrature amplitude modulation (QAM) process, the 3 dB bandwidth of the spectrum is narrowed down to 35 MHz. Half of the spectrum shaping is performed in the modulator and half in the demodulator section, in filters with cosine-shaped edges [5]. The filter in the modulation section also compensates the sin*x*/*x*-shaped spectrum of the digital modulation signal. The high data rate and the 16 possible QAM states make high demands on spectrum-shaping filters for optimum reception. Within the passband of the filters the magnitude of the transfer function should be undistorted and the group delay time constant.

Using the design approach and the production technology outlined above, the spectrum-shaping filters were manufactured as SAW filters with a center frequency of 140 MHz **(Fig. 3).** For the filter in our example, which has a bandwidth of 35 MHz and is intended for the demodulator section, the transfer function deviates by only 0.1 dB from its design value **(Fig. 4).** The group delay time is constant apart from a ripple of 1 ns. The measured and the designed impulse response of the filter show a good agreement at the specified zeros **(Fig. 5).** The lithium niobate filter chip is only 2.5 mm × 16 mm in size. The filter insertion loss is 26 dB across 50 Ω.

Fig. 7
Magnitude of the transfer function of the spectrum-shaping SAW filter for 2 Mbit/s digital radio link systems

a) Frequency response



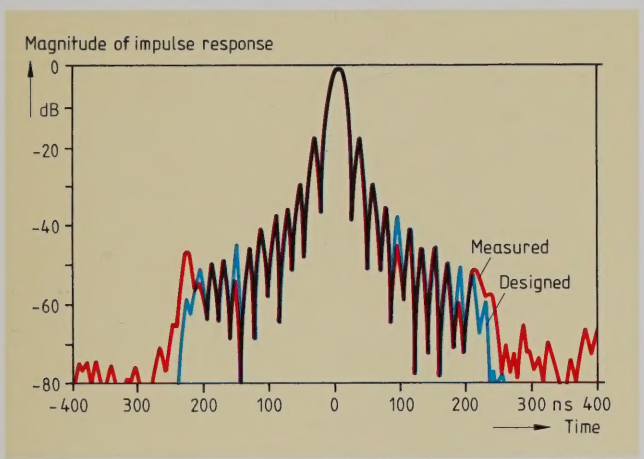


Fig. 5
Magnitude of the impulse response of a spectrum-shaping filter for the demodulator stage of a 140 Mbit/s digital radio link system

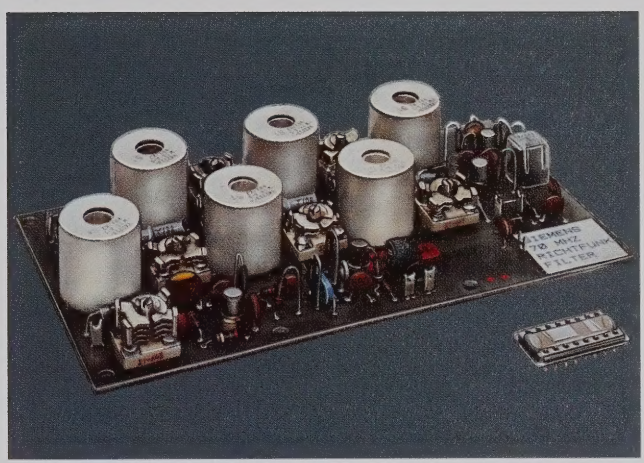
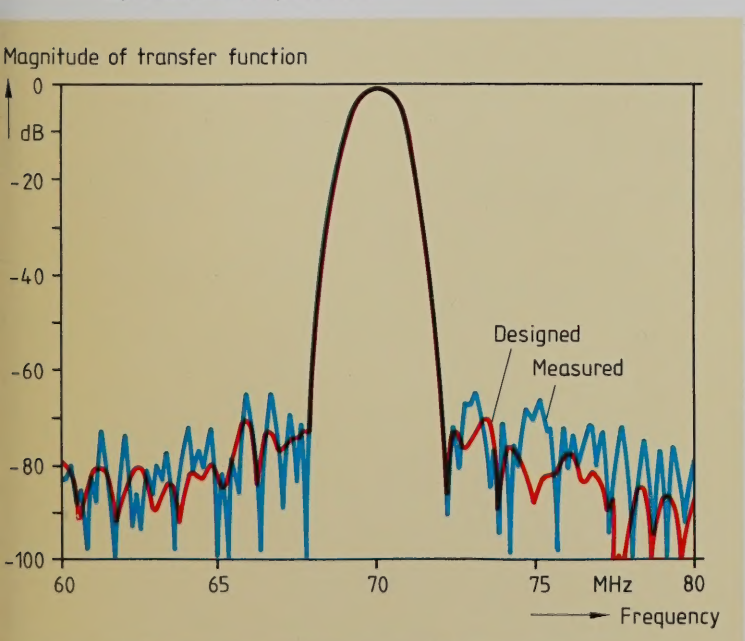


Fig. 6
Comparison of narrowband spectrum-shaping filters for 2 Mbit/s digital radio link systems: LC filter (back) and SAW filter on quartz substrate (front)

b) Details of the passband



Narrowband spectrum-shaping filter

A comparison of an LC filter with an SAW filter for 1 MHz bandwidth and 70 MHz center frequency shows that the LC filter requires selected, bulky and elaborately tuned LC circuits **(Fig. 6).** In contrast, SAW filters on quartz are miniaturized, precise and thermally stable.

An example of a spectrum-shaping filter for a digital radio link system with low bit rate shows the kind of precision which is attainable with quartz substrates. The stopband attenuation of the filter is 65 dB **(Fig. 7a).** The deviation of the measured transfer function from its design value is 0.01 dB **(Fig. 7b).** The group delay time is constant apart from a ripple of 2 ns. The insertion loss across 50 Ω is 38 dB. The filter chip is 4 mm × 20 mm in size.

The high precision of SAW filters on quartz results from the impedance conditions. For reasons of matching, significantly greater apertures were obtained for these transducers than for lithium niobate ones, which resulted in closer agreement with the models used for the design.

Apart from filtering, surface wave technology also offers new and to some extent unparalleled ways of signal delay in the µs region, of generating high frequency carrier signals with low phase noise and of ultra high speed signal processing.

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